QCD Results from the Tevatron

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Introduction

- QCD studies are an important part of the physics program of Tevatron experiments.
- QCD analyses provide an important test of pQCD calculations, constraints on proton PDFs, corrections on the theoretical models for hadronization/UE effects, and possibility to tune different MC generators.
- Almost any new physics (NP) involves QCD often a (huge) dominant background.
- Better understanding of QCD means improved sensitivity to NP.

Outline

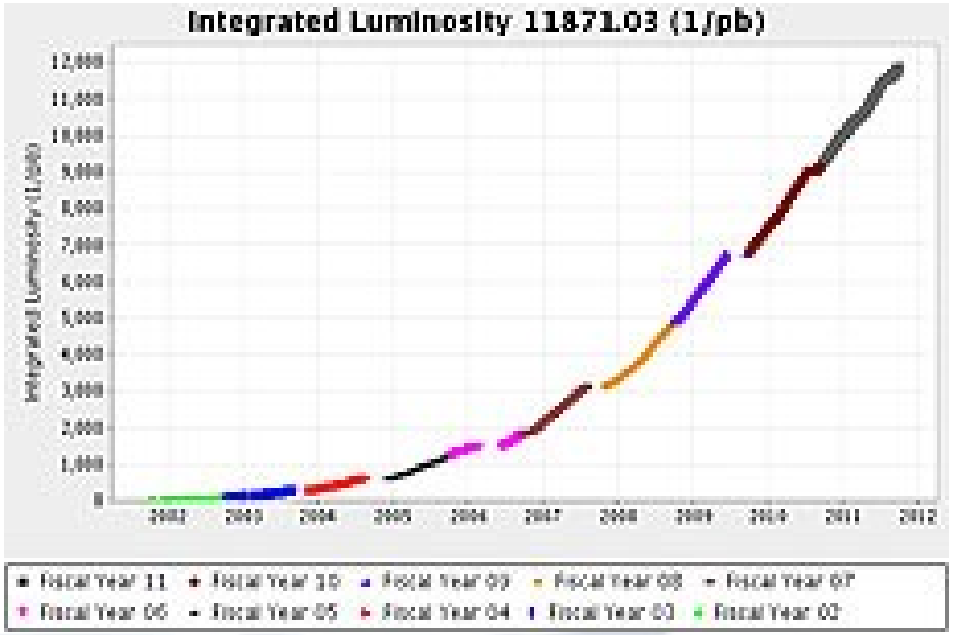
- Tevatron p-$\bar{p}$ collider, DØ and CDF detectors
- Three-Jet Mass Cross Section (DØ)
- Substructure of High P_T Jets (CDF)
- Azimuthal Decorrelations and Multiple Parton Interactions (DØ)
- Inclusive W+Jets Production Cross Sections (DØ)
- Inclusive Z+Jets and Z+b-jets Production Cross Sections (CDF)
- Ratio of Inclusive Cross Sections σ(Z+b-jet) / σ(Z+jet) (DØ)
- Exclusive Di-Photon Production (CDF)
- Prompt Isolated Di-Photon Production Cross Section (CDF)
- Summary

This talk will cover only a small fraction of all QCD results from the Tevatron.
More results can be found on:
http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm

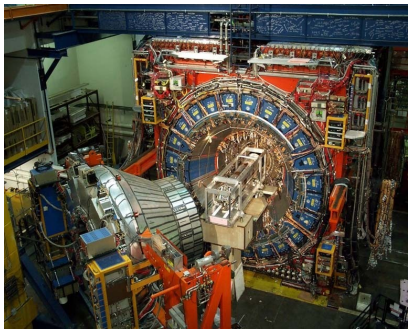
Tevatron p-$\bar{p}$ collider

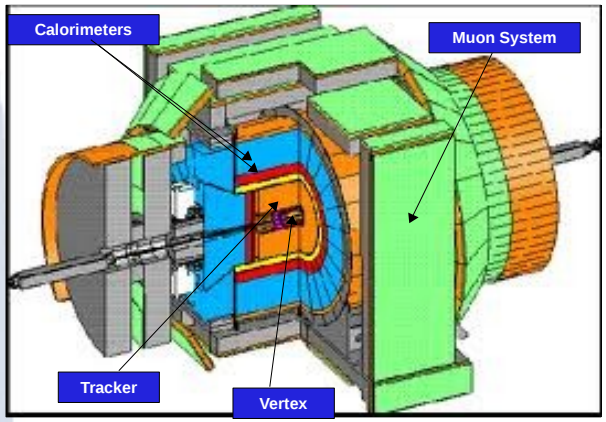
Run II (March 2001 – September 2011)

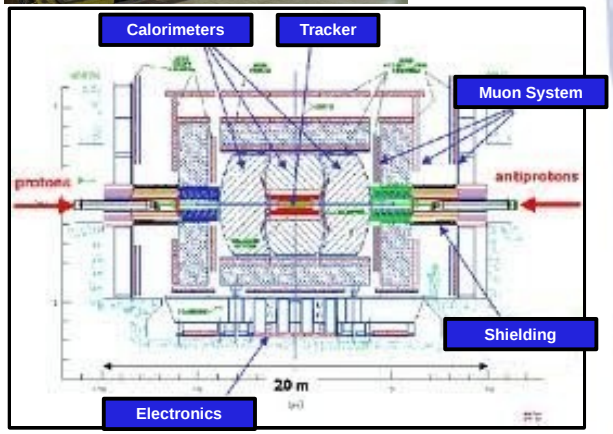
- Excellent Tevatron performance!
- Delivered over 11 fb^{-1} to each experiment
- Peak luminosity is 4.3×10^{32} cm^{-2} s^{-1}



CDF and DØ







Multi-purpose detectors

Common features

- Tracking in magnetic field
- EM and HAD calorimeters

Competitive advantages

- CDF: better momentum resolution
- DØ: finer calorimeter segmentation

- Silicon Vertex $|\eta| < 2\text{-}2.5$
- Drift Chamber $|\eta| < 1.1$
  1.4 T B Field
- Pb/Cu/Sci Calorimeter $|\eta| < 3.2$
- Muon Chambers $|\eta| < 1.5$

- Silicon Vertex $|\eta| < 3$
- Sci. fiber Tracker $|\eta| < 1.7$
  1.9 T B Field
- Lar/DU Calorimeter $|\eta| < 4$
- Muon Chambers $|\eta| < 2$

Data recorded with high efficiency (~ 90%)

Three-Jet Mass Cross Section

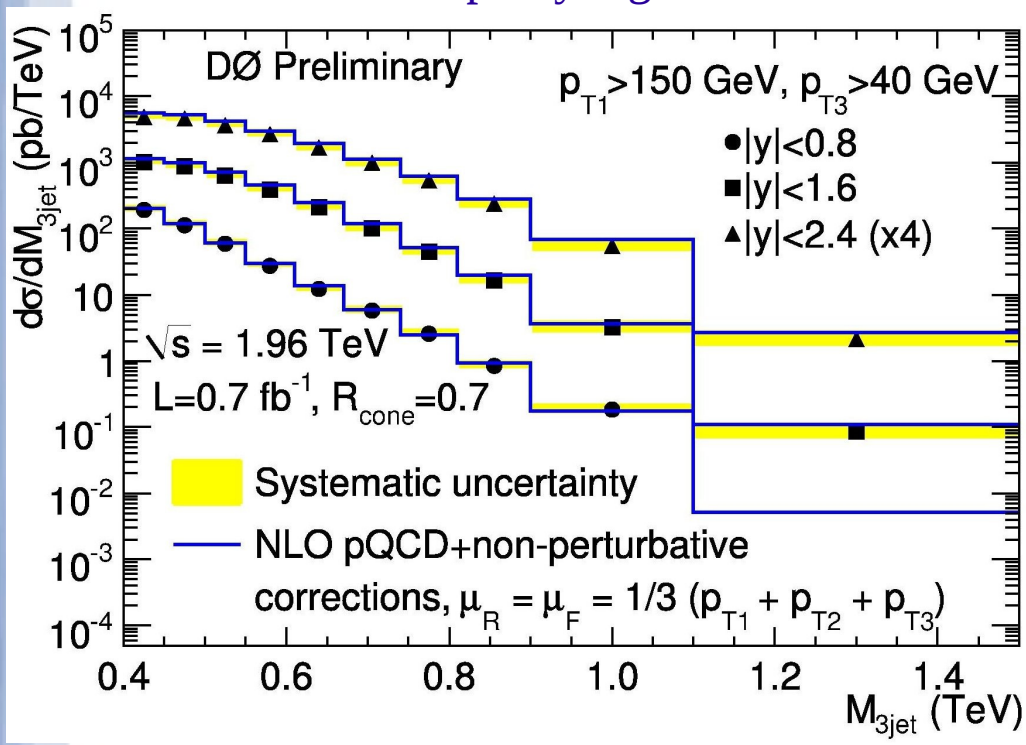
- The production of jets represents a dominant part of the total inelastic cross section in $p\bar{p}$ collisions at $s^{1/2}$=1.96 TeV.
- Measurements of jet properties can be used to test QCD predictions, to constrain PDFs and to look for NP beyond the SM model.
- Measurement of 3-jet cross section can be used to test NLO calculations.

Three-Jet Mass Cross Section (0.7 fb^{-1} DØ data)

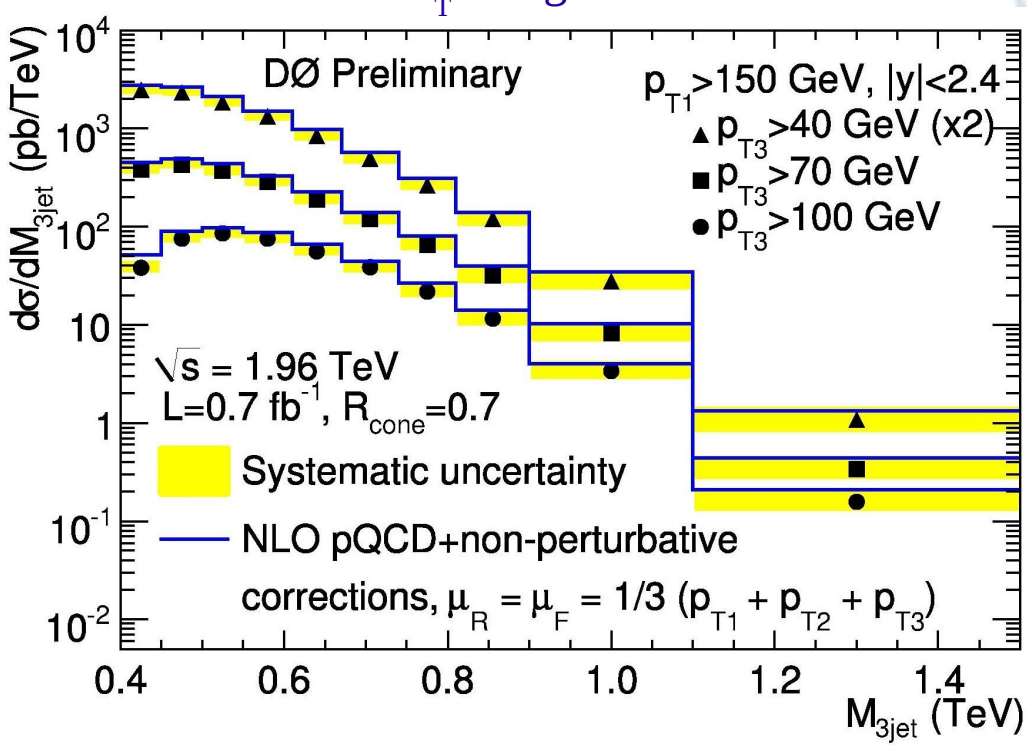
Phys. Lett. B 704, 434 (2011)

- Measured differential inclusive 3-jet cross sections a function of the M_{3jet} for events with well separated jets and $P_T^{jet1} > 150$ GeV/c.
- Data compared to NLO calculations (NLOJET++ MSTW2008NLO PDF set).
- NLO predictions corrected for non-perturbative effects (hadronization and UE) (PYTHIA Tune QW).
- Total systematic uncertainty: 20%-30% (dominated by JES, P_T resolution and luminosity).

3 rapidity regions



3 P_T^{jet3} regions



Three-Jet Mass Cross Section (0.7 fb^{-1} DØ data)

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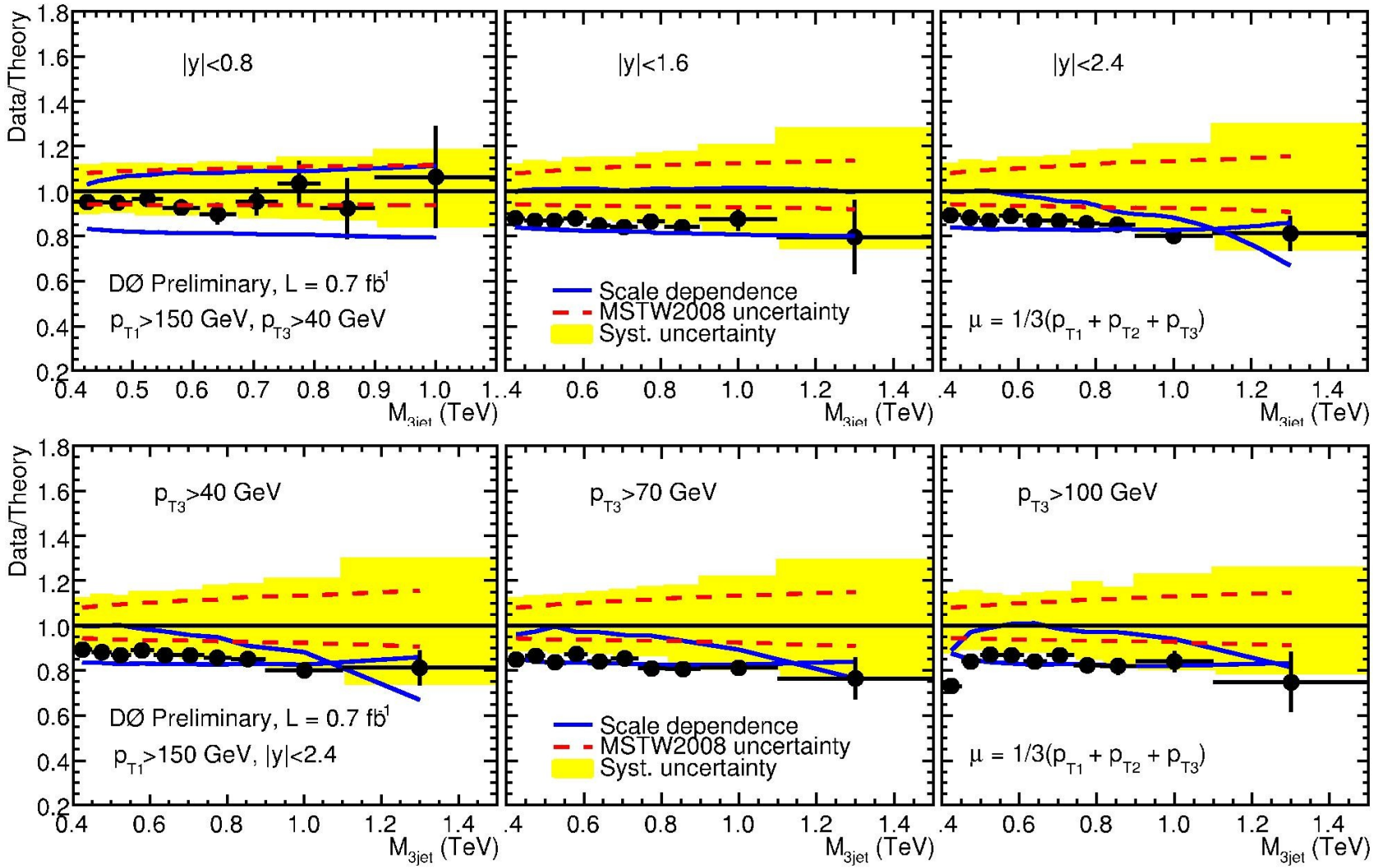


- Reasonable agreement between data and NLO (NLOJET++ with MSTW2008) in all cases within uncertainties.

Substructure of High P_T Jets

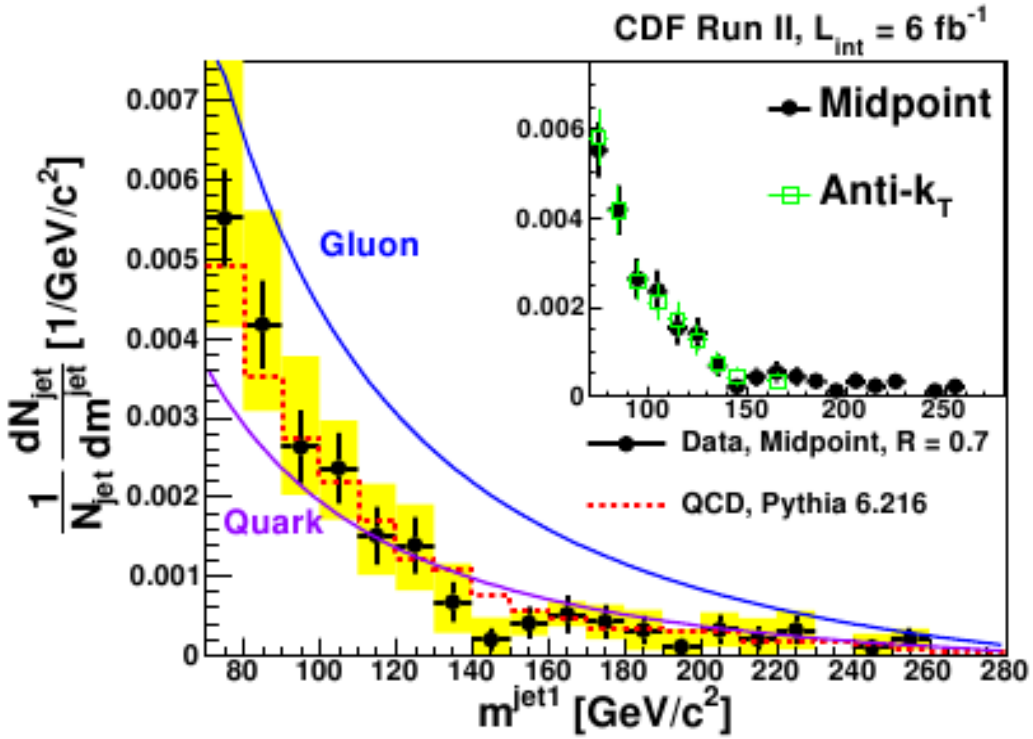
- Study of high P_T massive jets provides important test of pQCD
- Important background for various new physics models, Higgs searches and high P_T top-quark production.
- Particularly relevant is the case of heavy resonance decaying into high P_T top quarks that decay hadronically.
- The detected single jet shows a large mass and an internal substructure different from QCD jets.

Substructure of High P_T Jets (~6 fb^{-1} CDF data)

Jet Mass

arXiv:1106.5952v2 [hep-ex]

- Measured normalized jet mass distribution for jets with P_T > 400 GeV/c.



- Good agreement with PYTHIA prediction.
- Better agreement with quark jet function consistent with pQCD prediction: ~80% of high jet mass from quark fragmentation.
- Anti-k_T and Midpoint jets very similar mass distribution.

Substructure of High P_T Jets (~6 fb^{-1} CDF data)

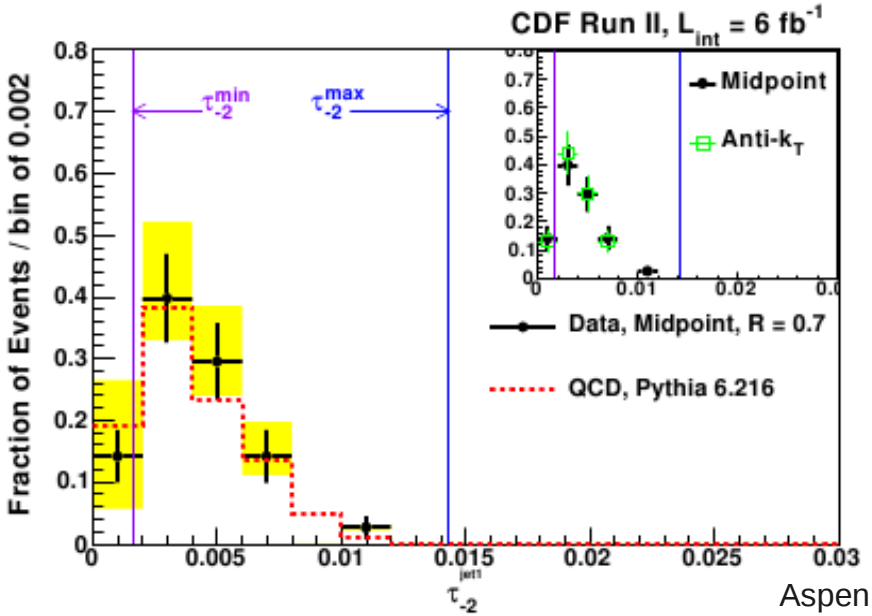
Angularity and Planar Flow

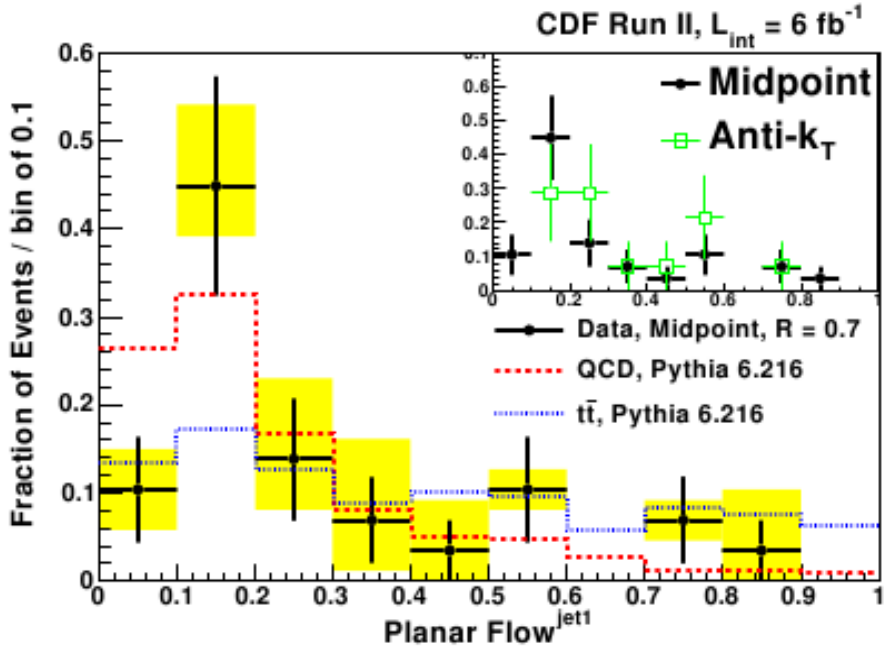
arXiv:1106.5952v2 [hep-ex]

- Both variable are IR safe and less dependent from jet algorithm.
- Expected to provide discrimination of heavy-particle jets and massive QCD jet:
  - Angularity is sensitive to degree of symmetry of energy deposition
  - Planar flow distinguishes planar (P_f~1) from linear configuration (P_f~0)

$$P_f \equiv \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2} \qquad I_w^{kl} = \frac{1}{m^{jet}} \frac{\sum_{i\in jet} p_{i,k}}{E_i} \frac{p_{i,l}}{E_i}$$

$$\tau_{-2}(R, P_T) \equiv \frac{1}{m^{jet}} \sum_{i\in jet} E_i \sin^{-2}\theta_i [1-\cos\theta_i]^3$$

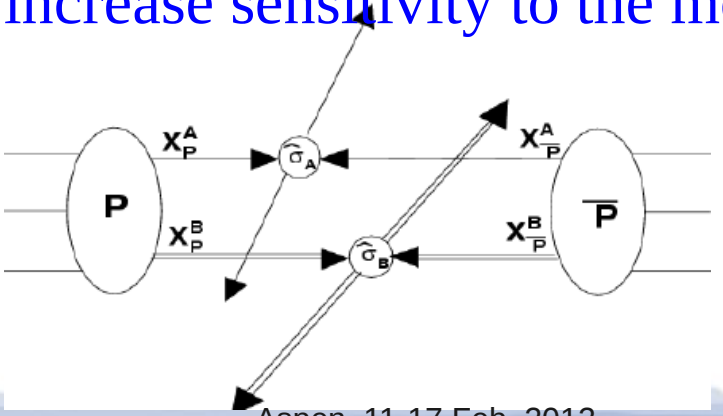




- Good agreement with PYTHIA prediction.
- Anti-k_T and Midpoint good agreement with each other.

Azimuthal Decorrelations and MPI in γ+2/3 Jets

- Study Multiple Parton Interactions (MPI) in high P_T regime (P_T^{jet} >15 GeV) can give complementary information about proton structure.
- Also a better understanding of non-pQCD.
- Estimate of contributions from DP interactions is important to study backgrounds for many rare processes.
- Measuring differential cross sections in γ+2(3)jet events with high P_T jets can be used to tune MPI models.
- Different P_T^{jet} bins increase sensitivity to the models.

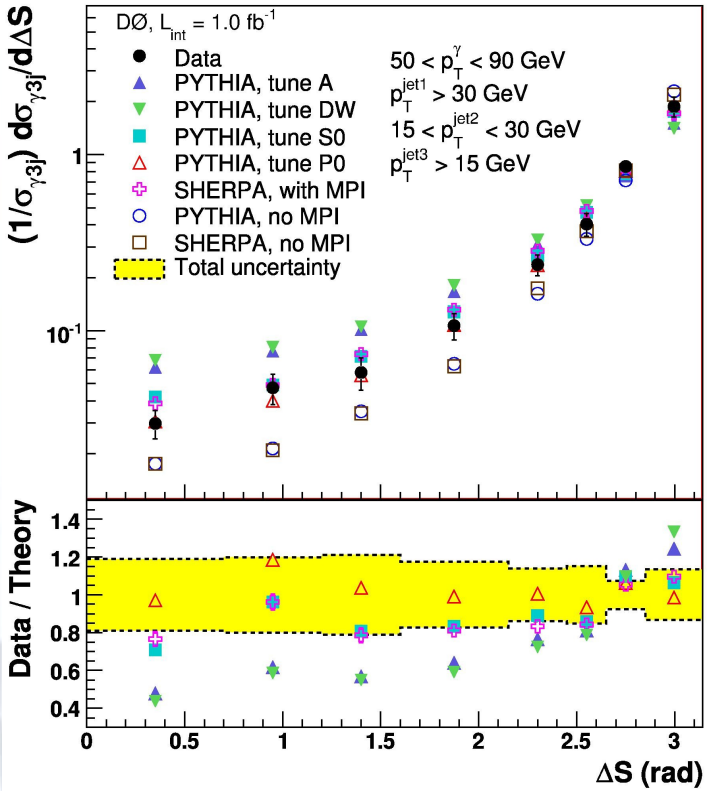


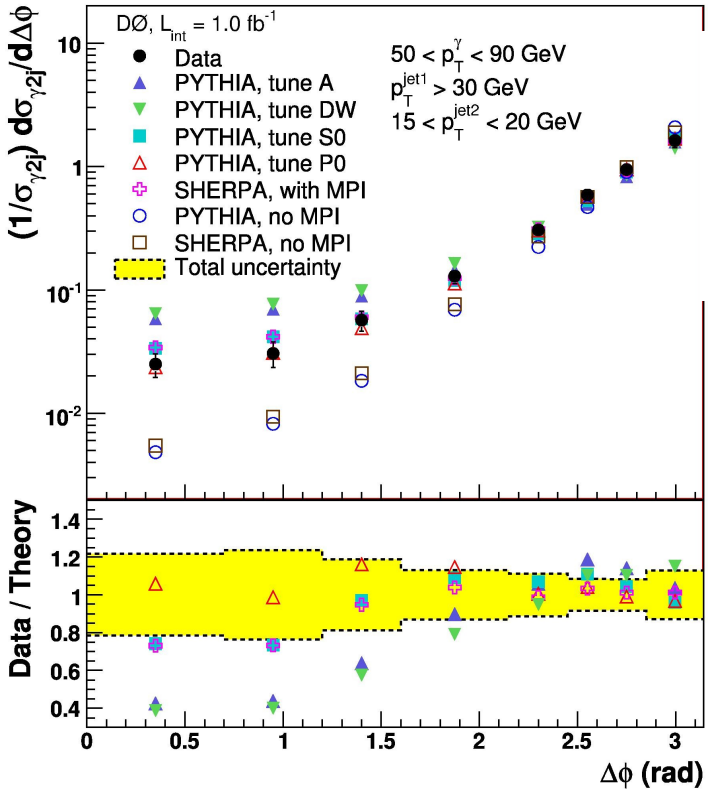
Azimuthal Decorrelations and MPI in γ+2/3 Jets (~1 fb^{-1} DØ data)

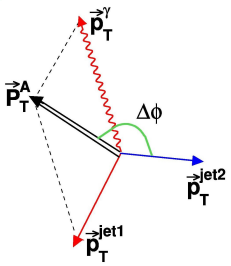
Phys. Rev. D 83, 052008 (2011)

- Measured 4 normalized differential cross sections:
  - $\Delta\Phi$ (P_T^A, P_T^{jet2}) in 3 bins of P_T^{jet2} (15-20, 20-25, 25-30 GeV)
  - ΔS (P_T^A, P_T^B) in 1 bin of P_T^{jet2} (15-30 GeV)

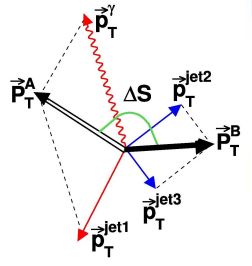
Angular distribution sensitive to DP events



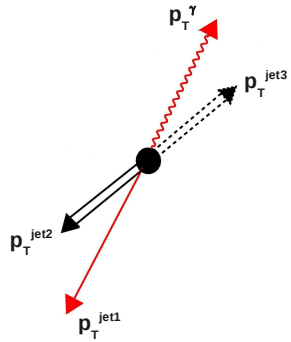




γ+2 jet events



γ+3 jet events

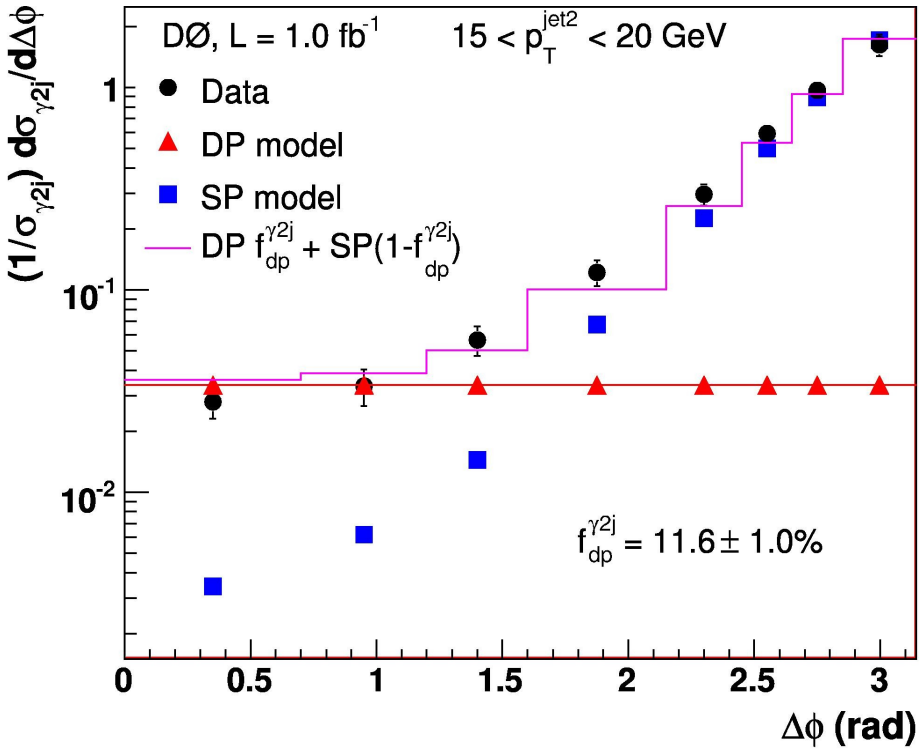


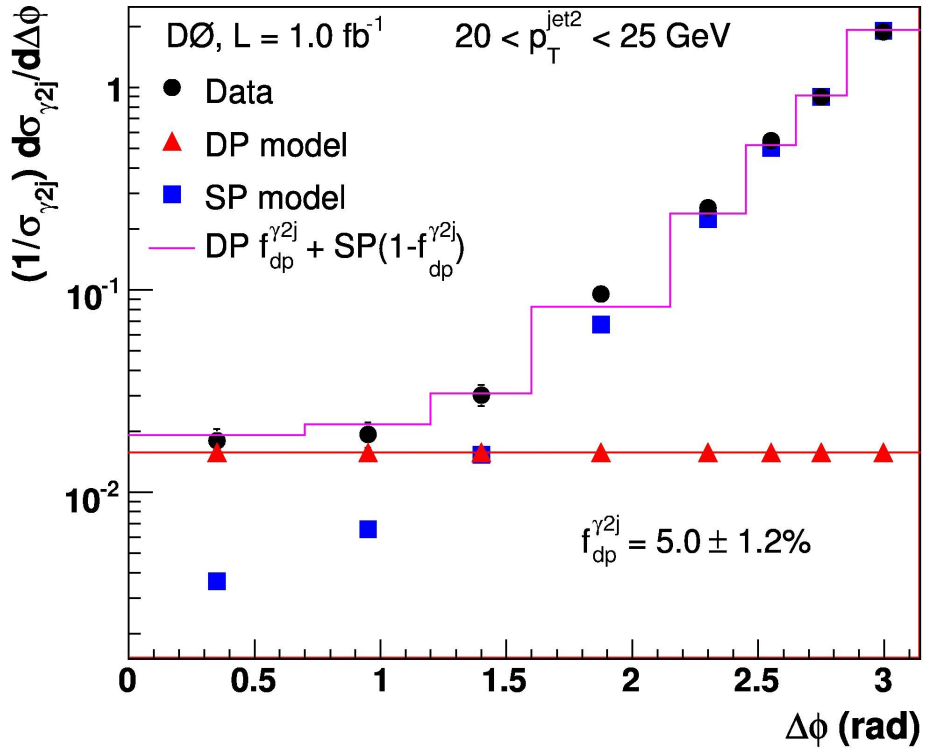
DP events

- Large difference between SP models and data: presence of DP events in the data sample.
- Data are close to Pythia tune Perugia (P0), S0 and Sherpa with MPI tunes.

Azimuthal Decorrelations and MPI in γ+2/3 Jets (~1 fb^{-1} DØ data)

Phys. Rev. D 83, 052008 (2011)





- The sum of the SP and DP predictions (weighted with their respective fractions) reproduces the data well.

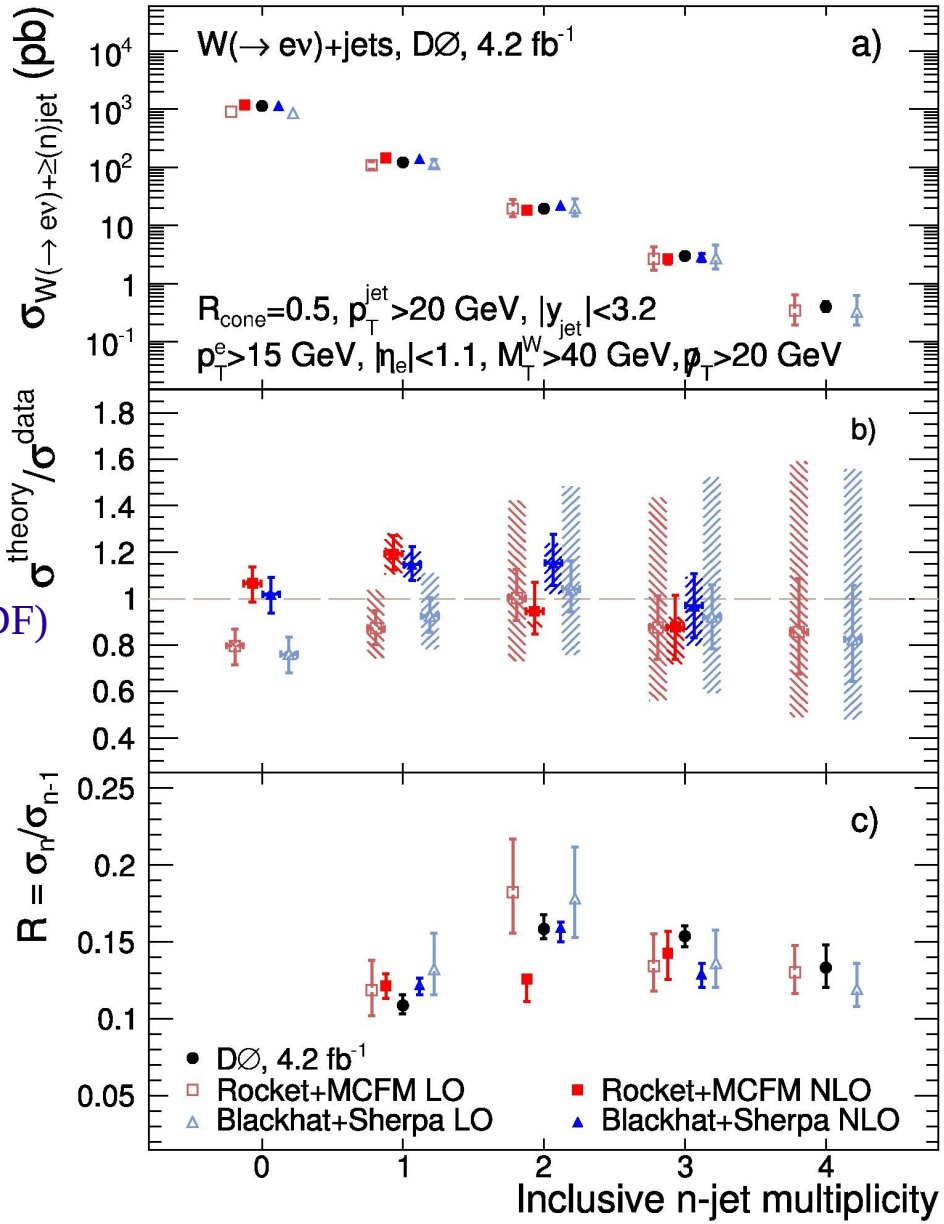
W/Z+Jets

- Measurements of V boson plus jets production are fundamental test of pQCD predictions in multijet environment:
  - Presence of W/Z ensure high $Q^{2.}$
  - Leptonic final state provides clean signature and low background.
  - High statistics allows precision tests.
- Test and tune Monte Carlo models:
  - Experimental data are used to validate many MC tools available.
- W/Z+HF production sensitive to PDFs HF content.
- W/Z+bb in particular can be the dominant background in:
  - top, Higgs, SUSY and other NP scenarios

Inclusive W+Jets production (4.2 fb^{-1} DØ data)

Phys. Lett. B **705,** 200 (2011)

- Measured total inclusive W+jets cross section for each jet multiplicity
  W → eν + n jet (n=1-4) as final state
- First study of W+4 jet production
- First comparison with NLO W+3 jet cross section predictions.
- Data compared to LO and NLO calculations (Blackhat+Sherpa and Rocket+MCFM, MSTW2008 PDF)
- Parton-to-particle correction (had. and UE event) (SHERPA , CTEQ6.6 PDF set)
  - ~10% (25% in highest P_T^{jet} bin)



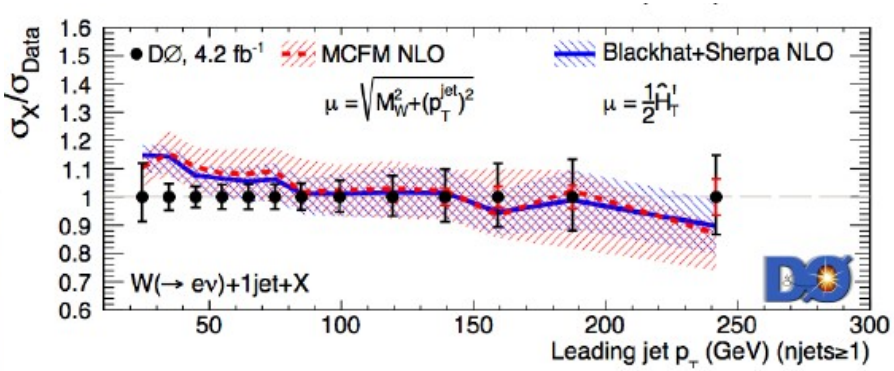
- Good agreement between data and theory
  - except for 1-jet bin

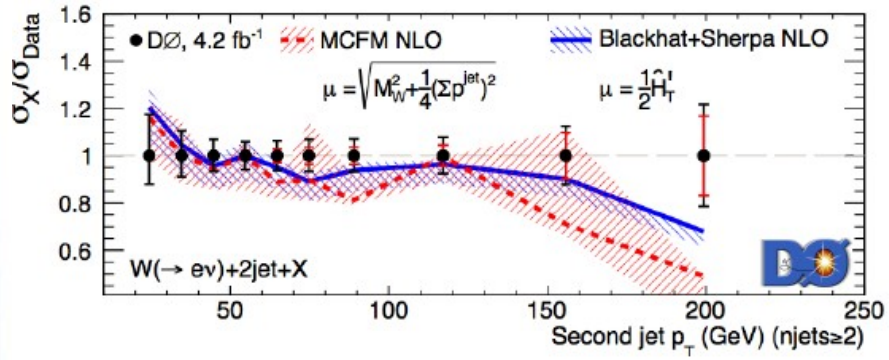
Inclusive W+Jets production (4.2 fb^{-1} DØ data)

- Measured differential cross sections for each jet multiplicity
- All are normalized to the measured total inclusive W boson cross section:

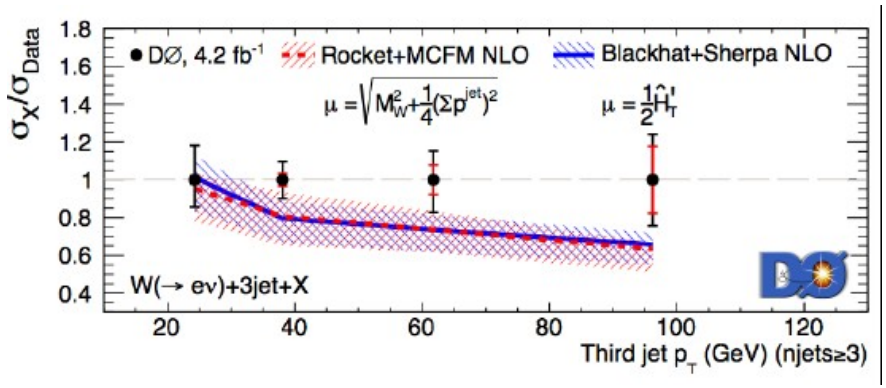
$$\sigma_W = 1132 \pm 1\,(stat)^{+43}_{-84}\,(syst) \pm 69\,(lumi)\,pb$$

Phys. Lett. B **705,** 200 (2011)

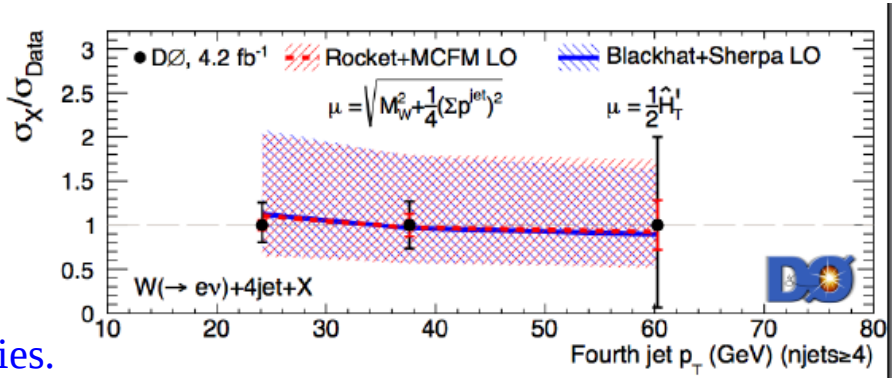




- Data agree well with both NLO calculations
- Data uncertainties are comparable to theoretical uncertainties.



- NLO calculations smaller than measurements
- Some disagreement in shape and normalization.



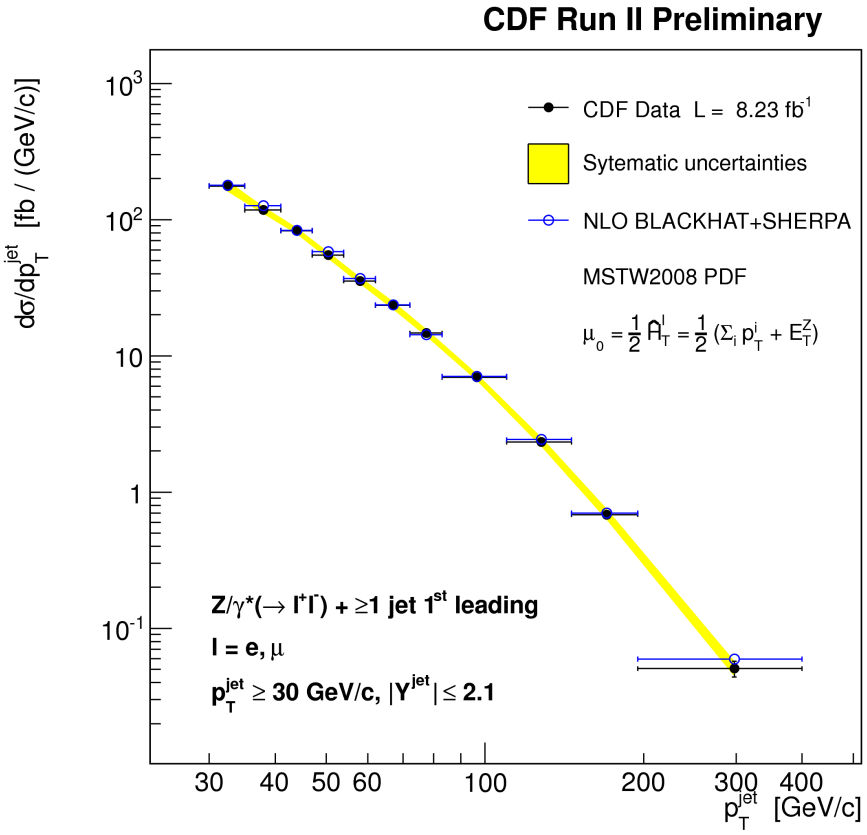
- Only LO calculation available at Tevatron right now.
- Good agreement, but large scale uncertainties.
- NLO prediction needed for more robust comparison

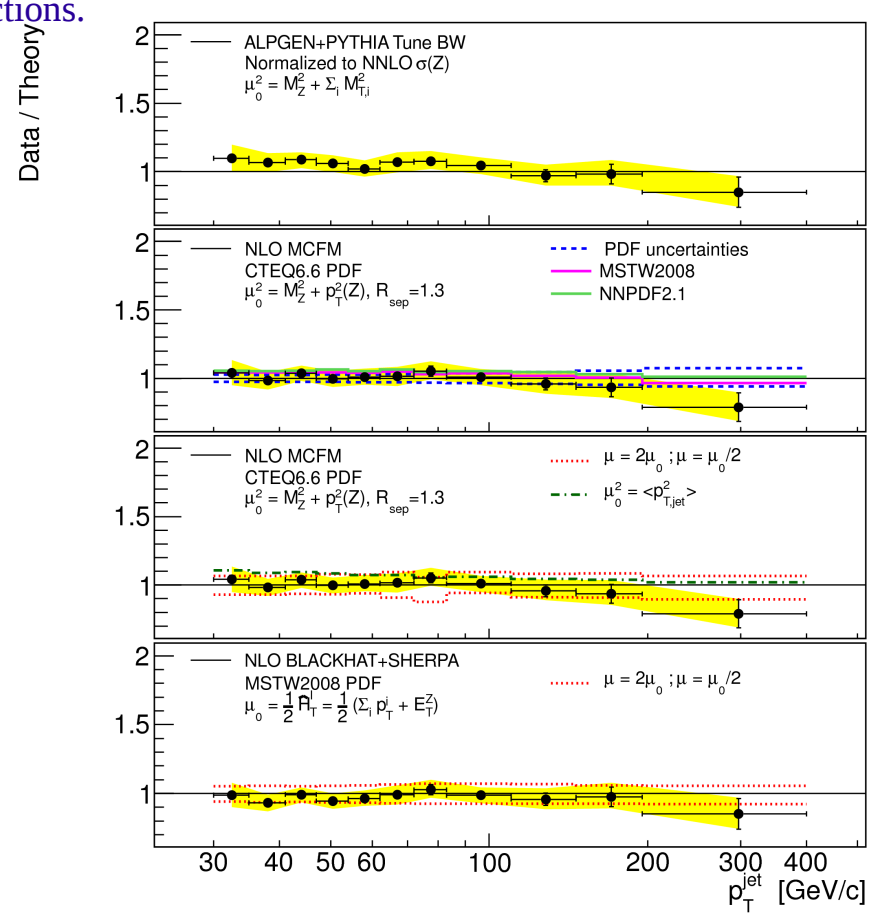
Z/γ*+jets Production (8.2 fb^{-1} CDF data)

- Measured jet cross section in Z/γ^* +≥1,2,3 jets
- Performed independently for $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ in the same kinematic region to allow combination.
- Results compared to NLO pQCD predictions + non-pQCD corrections.

CDF note 10216

CDF note 10394





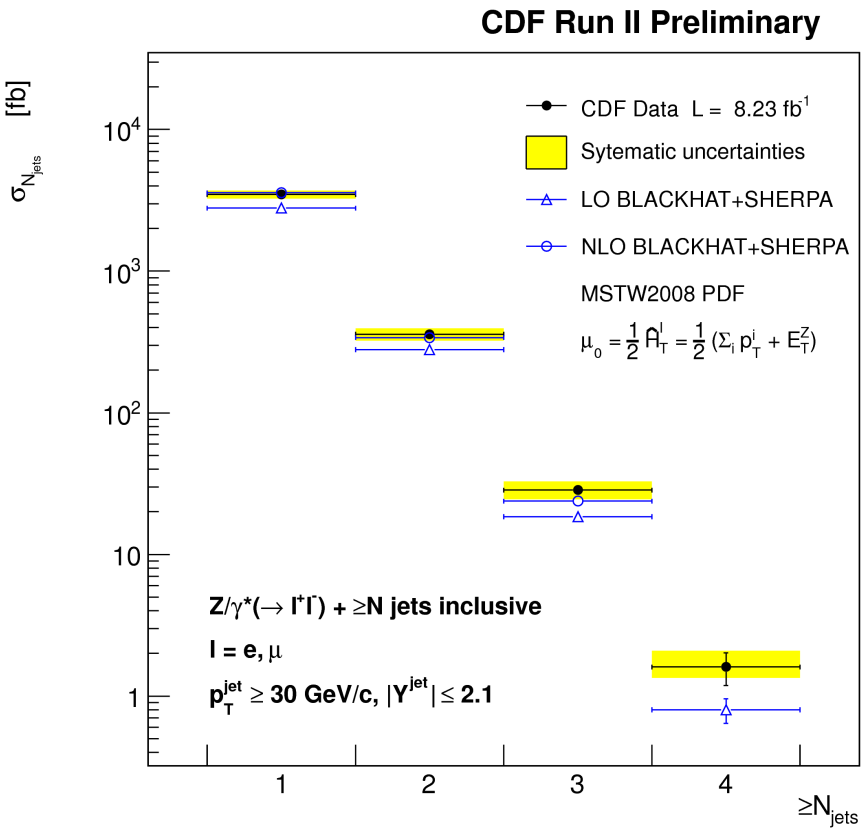
- Good agreement with NLO pQCD predictions including non-pQCD corrections estimated from PYTHIA.
- BLACKHAT differs from MCFM prediction for the different choise of the scale: improvement in high P_T^{jet} tails.
- New tuning of ALPGEN+PYTHIA Perugia 2011 gives an improved agreement. Work in progress for the comparison.
- PDFs errors are quite small respect to the scale uncertainties.

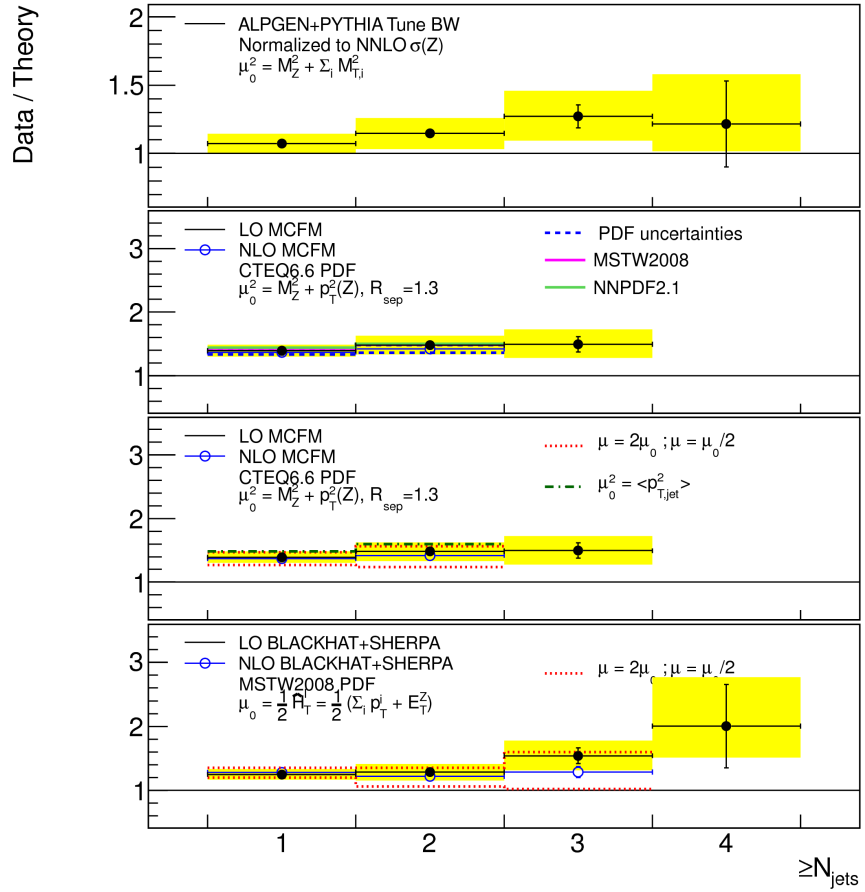
Z/γ*+jets Production (8.2 fb^{-1} CDF data)

CDF note 10216

CDF note 10394

- Measured total inclusive cross section as a function of jet multiplicity.
- Results compared to NLO pQCD predictions + non-pQCD corrections.



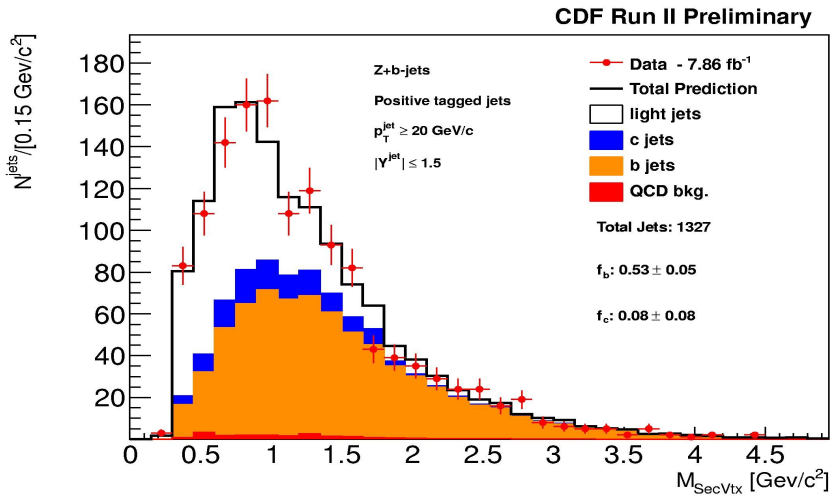


- Good agreement with NLO pQCD predictions including non-pQCD corrections from PYTHIA.
- Only LO predictions for Z+4 jets for Tevatron (Available at the LCH).

Z+b-jet Production (~8 fb^{-1} CDF data)

CDF note 10594

- Measured ratios of b-jet cross section with respect to inclusive Z and integrated Z+jets cross section for events with a Z boson ($66 \leq M_{l+l-} \leq 116$ GeV/c^2) and jets ($P_T \geq 20$ GeV/c and $|y| \leq 1.5$)



Binned maximum likelihood fit to data to find fractions from different jet flavors.

$$\frac{\sigma_{Z\_bjet}}{\sigma_Z} = 0.293 \pm 0.030^{stat} \pm 0.036^{syst}\%$$

$$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}} = 2.31 \pm 0.23^{stat} \pm 0.32^{syst}\%$$

To compare to NLO predictions with MCFM

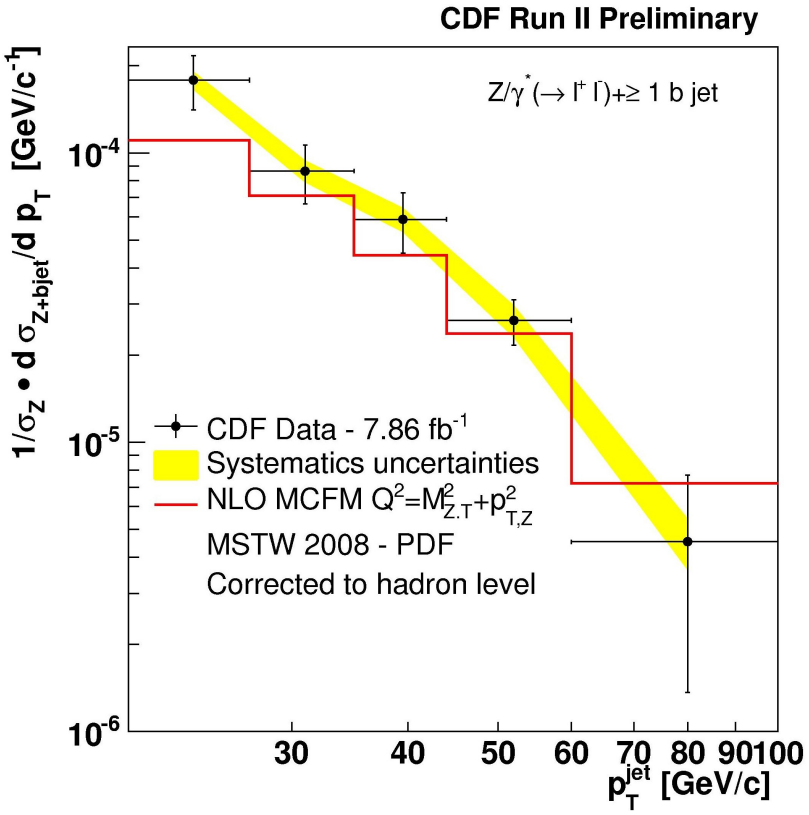
	$Q^2 = m_Z^2 + p_{T,Z}^2$	$Q^2 = < p_{T,jet}^2 >$
$\frac{\sigma_{Z\_bjet}}{\sigma_Z}$	0.24 %	0.32 %
$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}}$	1.8 %	2.2%

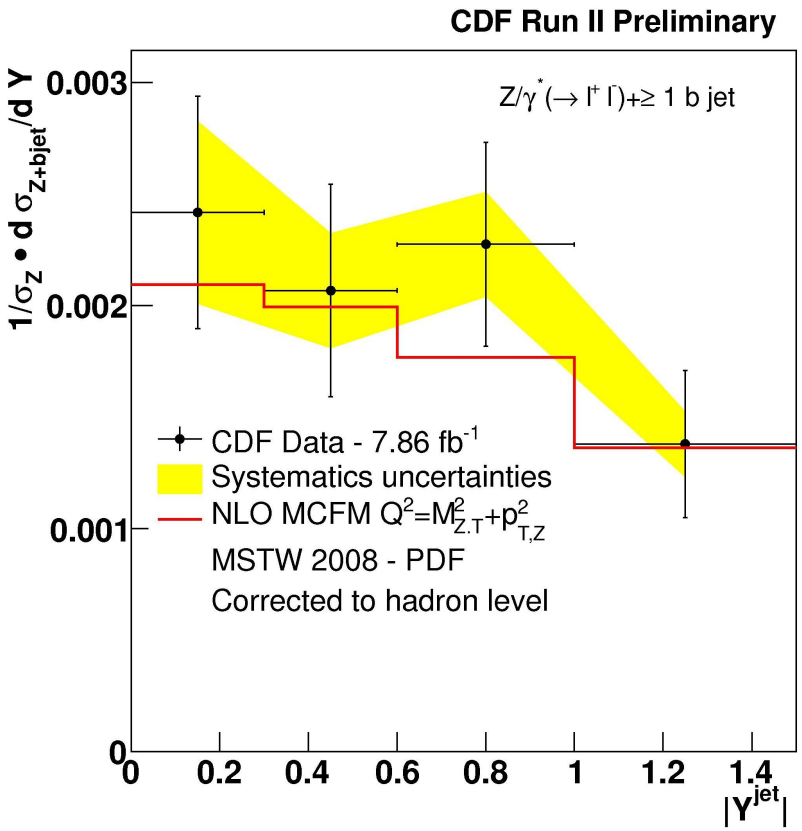
- Measurements in agreement with MCFM predictions within large uncertainties.
- Comparison with predictions using different renormalization and factorization scales shows measurements close to those with lower scales.

Z+b-jet Production (~8 fb^{-1} CDF data)

CDF note 10594

- Measured differential cross sections as a function of jet P_T and rapidity.
- Statistical uncertainty ~ 20%.
- Results compared to NLO predictions (MCFM with different renormalization and factorization scales and PDF sets) corrected for non-pQCD effects (ALPGEN+PYTHIA Tune P2011).





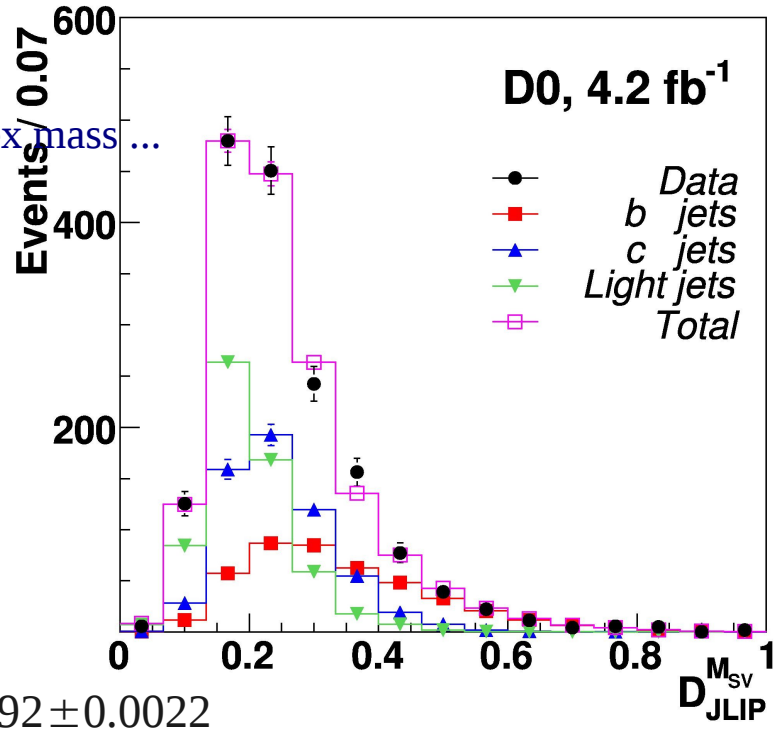
- Measurements in agreement with MCFM predictions but affected by large uncertainty.

Z+b jet/Z+jet cross section (4.2 fb^{-1} DØ data)

Phys. Rev. D 83, 031105(R) (2011)

- Measured the ratio of the cross section for Z boson production in association with at least one b-jet to inclusive Z+jet cross section
  $Z \rightarrow e^+e/^-\mu^+\mu^-$ and jets (Midpoint R=0.5) with P_T>20 GeV and $|\eta|$ <2.5 as final states
- Measurement of the ratio → cancellations of many systematic uncertainties
  → more precise comparison with theoretical calculations
- Measurements uses Neural Network algorithm to enrich data with b-jets. Inputs: B lifetime, secondary vertices, vertex mass ...
- Extract b-composition in data using a fit to Discriminant Jet Lifetime Probability (D_{JLIP})

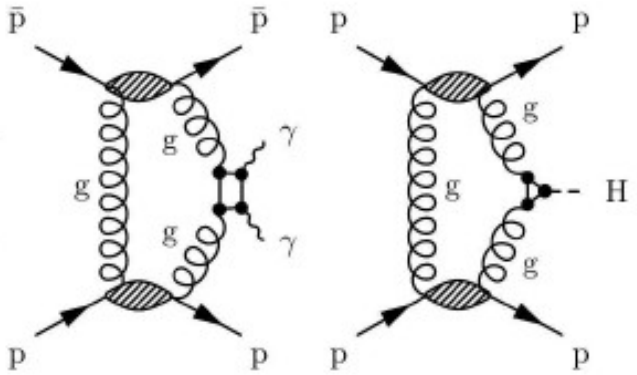
$$\frac{\sigma(Z+b\ \ jet)}{\sigma(Z+jet)} = 0.0193 \pm 0.0022(stat) \pm 0.0015(syst)$$



- Consistent with NLO MCFM calculations: 0.0192 ± 0.0022
  (MSTW2008 PDF set and renormal. and factoriz. scales at M_Z)

Exclusive γγ Production

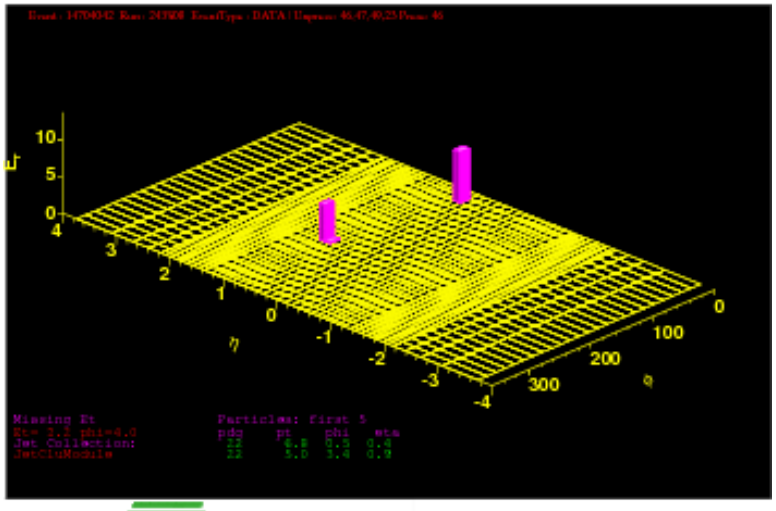
- Observation of exclusive γγ production is an important test of QCD theory of exclusive Higgs production at LHC.
- At the Tevatron, the exclusive Higgs cross section is too small.

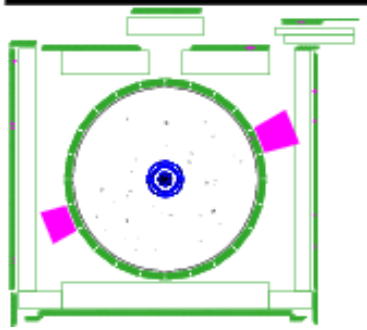


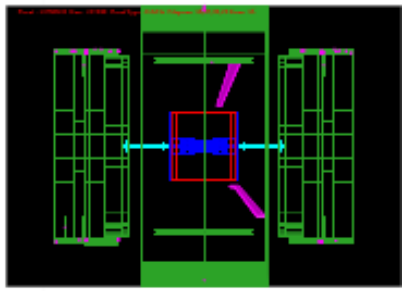
Exclusive γγ Production (1.1 fb^{-1} CDF data)

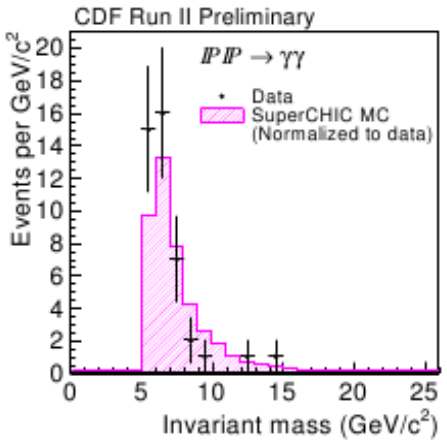
- Observed 43 events of exclusive photon pair production.
- Find: $\sigma = 2.48 \pm 0.42(stat) \pm 0.41(syst)pb$
- CDF also observed exclusive Dijet and χ_C production.

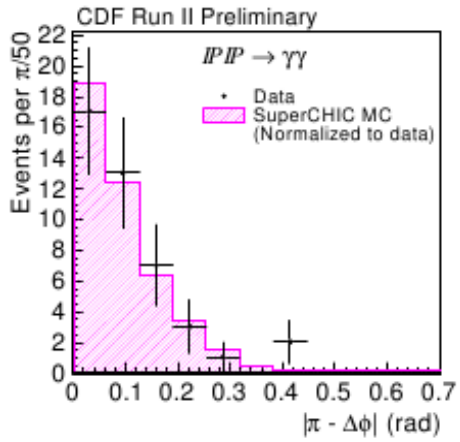
arXiv:1112.0858 [hep-ex]

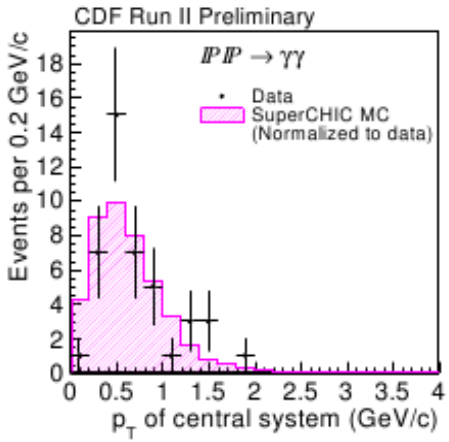


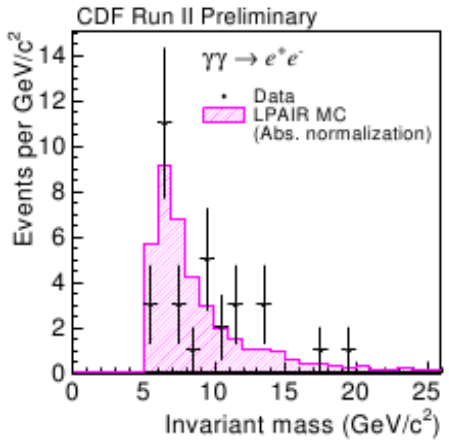












- In agreement with the only theoretical prediction based on the double pomeron process $IP + IP \rightarrow \gamma + \gamma$

Prompt Diphoton Production

- Large irreducible background for low mass Higgs search and new physics (new heavy resonances) .
- Test of pQCD and soft-gluon resummation method in theoretical calculation.

Diphoton differential cross section (~5.4 fb^{-1} CDF data)

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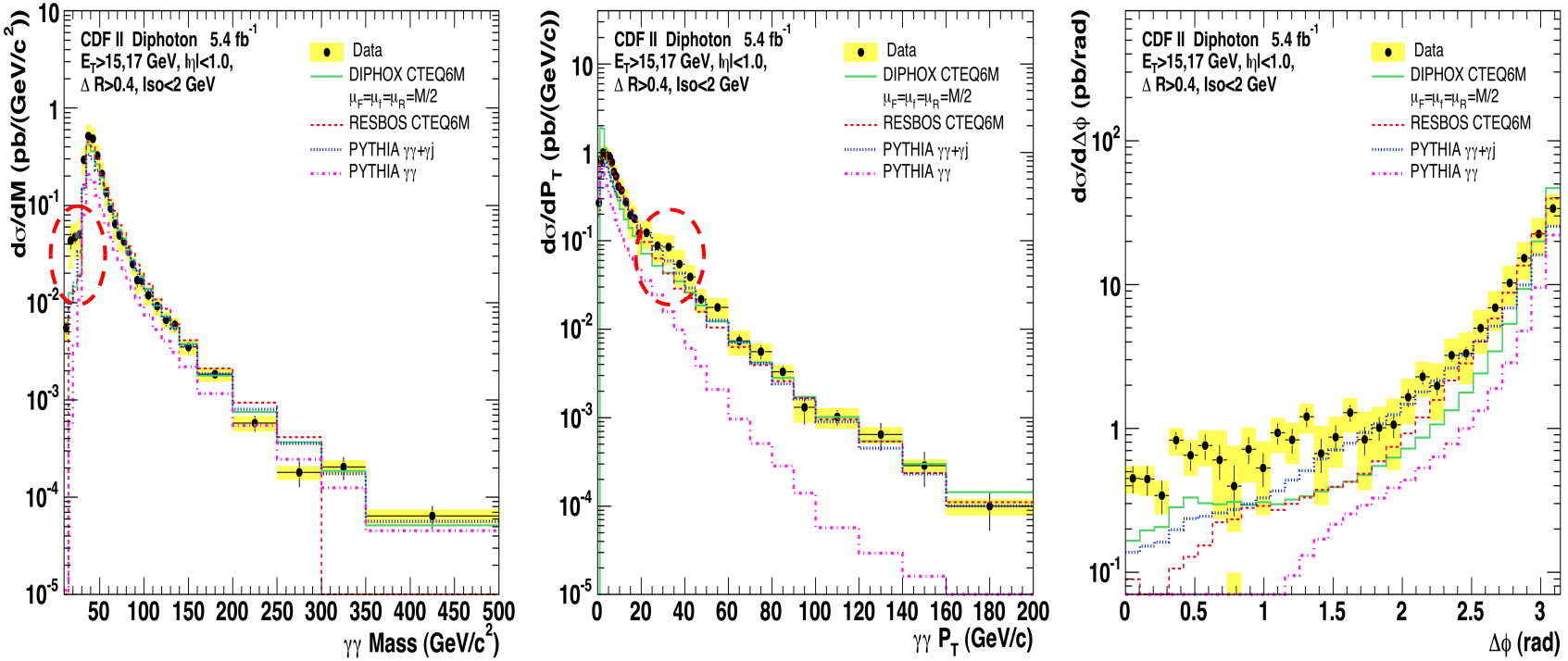
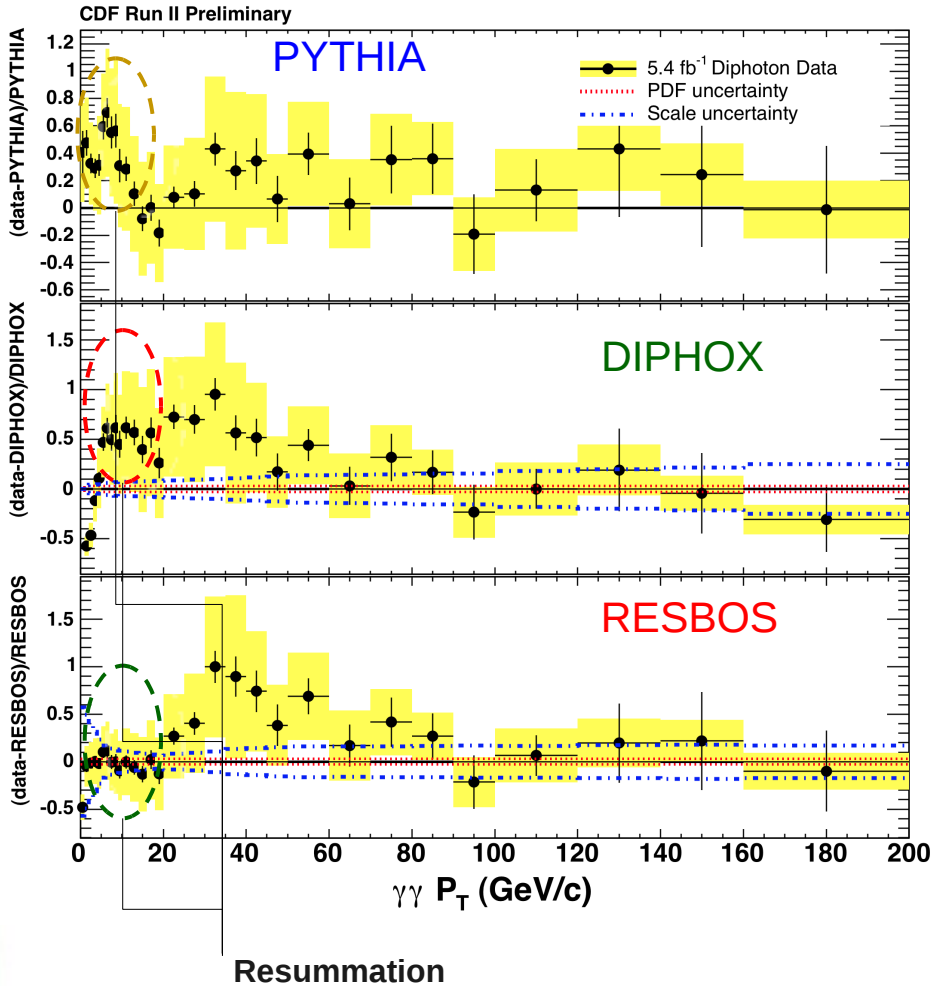
- Measured differential cross section as a function of $M_{\gamma\gamma}$, $P_T^{\gamma\gamma}$ and $\Delta\Phi$.
- Results compared with:
  - NLO DIPHOX including parton fragmentions into photons.
  - RESBOS with analytical initial state soft-gluon resummation.
  - PYTHIA with parton showering, ISR and FSR.

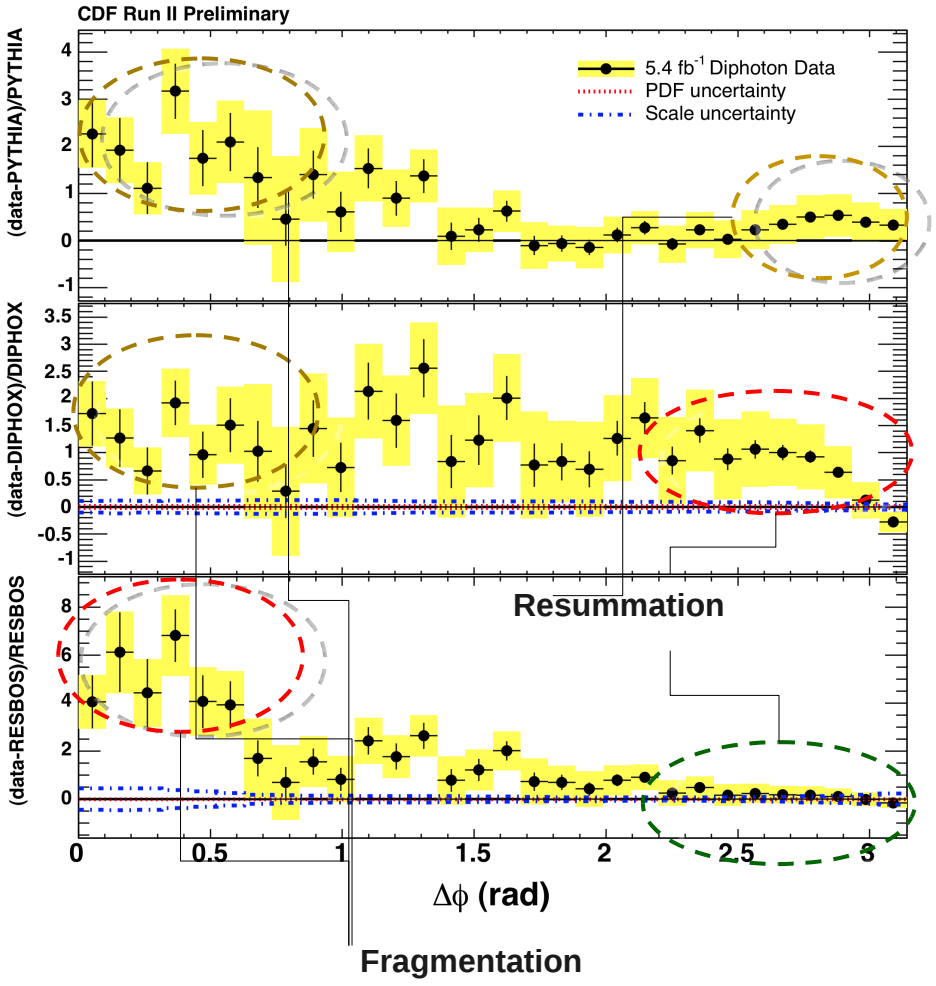


- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c^2
- Resummation important for $P_T(\gamma\gamma)$ < 20 GeV/c.
- Fragmentation causes excess of data over theory for $P_T(\gamma\gamma)$ =20–50 GeV/c ("Guillet shoulder")
- Resummation important for $\Delta\Phi_{\gamma\gamma}$ > 2.2 rad.

Diphoton differential cross section (~5.4 fb^{-1} CDF data)

Vertical axis scales are not the same





- In general all three calculations underestimate data in those regions where gluon interactions and associated fragmentation of quarks into photons are expected to be important.
- DIPHOX fails to reproduce data in those sensitive regions although explicitly includes a fragmentation model.
- Low transverse momentum and large azimuthal difference where resummation is important, are best described by RESBOS as the analytical resummation is implemented in this calculation.

Summary

- QCD studies are an important part of Run II physics program at the Tevatron. Better knowledge of QCD is crucial for the Tevatron and also for the LHC.
- QCD analysis are an important test for QCD calculations and constraints on proton PDFs, NLO + HO corrections, resummations,fragmentation effects and ISR models. Most of QCD channels are directly sensitive to new physics.
- QCD results are, in general, in good agreement with theory predictions within the errors. Some processes (photon/W + jet production) still require an improvement in theoretical predictions .
- Tevatron shut down last year, but analysis are still in progress. CDF and DØ are moving toward precision QCD measurements based on all data samples in excess of 9 fb^{-1}.
- More new physics results at next Moriond and DIS conferences. Stay tuned!

WORK IN PROGRESS

STAY TUNED